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## An integrative approach to product development—A skin-care cream

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### ABSTRACT

An integrative approach, involving marketing and management issues on the business side, and product design and prototyping on the technical side, is proposed for the development of chemical-based products. For the former, objective-time chart, RAT<sup>2</sup>IO modules and workflow diagrams are used for project management. For the latter, the integration of experiments, modeling and synthesis expedites product conceptualization and prototyping. Tasks for which chemical engineers are expected to play a key or a supporting role are discussed. An industrial application – the development of a skin-care cream is described alongside the procedure in order to illustrate the myriad issues in product development. In addition to the traditional engineering problems such as process and equipment design, product characterization, performance evaluation, and stability tests are also included as an integral part of this approach.

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### 1. Introduction

Spurred by a changing global business environment, both industrial and academic leaders have been urging the chemical engineering community to expand our focus from commodity to high-value-added products and from process design to product development. These efforts have gradually taken roots. A large number of research papers (Bagajewicz, 2007; Street, Woody, Ardila, & Bagajewicz, 2008; Wibowo & Ng, 2002; among others), review articles (Gani, 2004a; Hill, 2004; Wintermantel, 1999), textbooks (Cussler & Moggridge, 2001; Seider, Seader, & Lewin, 2004) and monographs (Bröckel, Meier, & Wagner, 2007; Ng, Gani, & Dam-Johansen, 2007) were devoted to the understanding of product development, and formulation of the relevant techniques.

The wide variety of activities in product development was summarized in a table by Ulrich and Eppinger (2004), a modified version of which is presented in Fig. 1. These activities span three phases in time – **product conceptualization, detail design and prototyping**, and **product manufacturing and launch** – and can be classified by *job function* in terms of **management, sales and marketing, research and design, manufacturing, and finance and economics**. The activities can also be grouped into various

*unit tasks*, which may involve several job functions and last over more than one development phase. For example, economic analysis includes activities in both phase II and phase III, and involves manufacturing as well as finance and economics. Of particular interest are those activities, italicized in Fig. 1, in product development that require the input of a chemical engineer. The execution of other activities within the same unit task may involve marketing and management. The key question is how to execute these unit tasks in a systematic manner to minimize the amount of time, effort and money for the development of chemical-based products. The rest of the issues in Fig. 1 such as product promotion and business management belong to other disciplines and will not be discussed in this article.

To formulate such a product development procedure, we will focus on a specific class of products—skin-care creams. Various issues related to product conceptualization of creams and pastes have been discussed by Wibowo and Ng (2001). For example, the quality factors such as sensorial, rheological, mechanical, and physicochemical have been classified. These quality factors are related to the material properties such as viscosity, dielectric constant, and so on, as well as to how the constituents are assembled to form the microstructure of the product, as characterized by structural attributes such as particle or droplet size distribution, phase volume fraction, and particle shape. An understanding of the relationships between product performance, and material properties and structural attributes enables the designer to select the proper ingredients and design the manufacturing process to obtain a prod-

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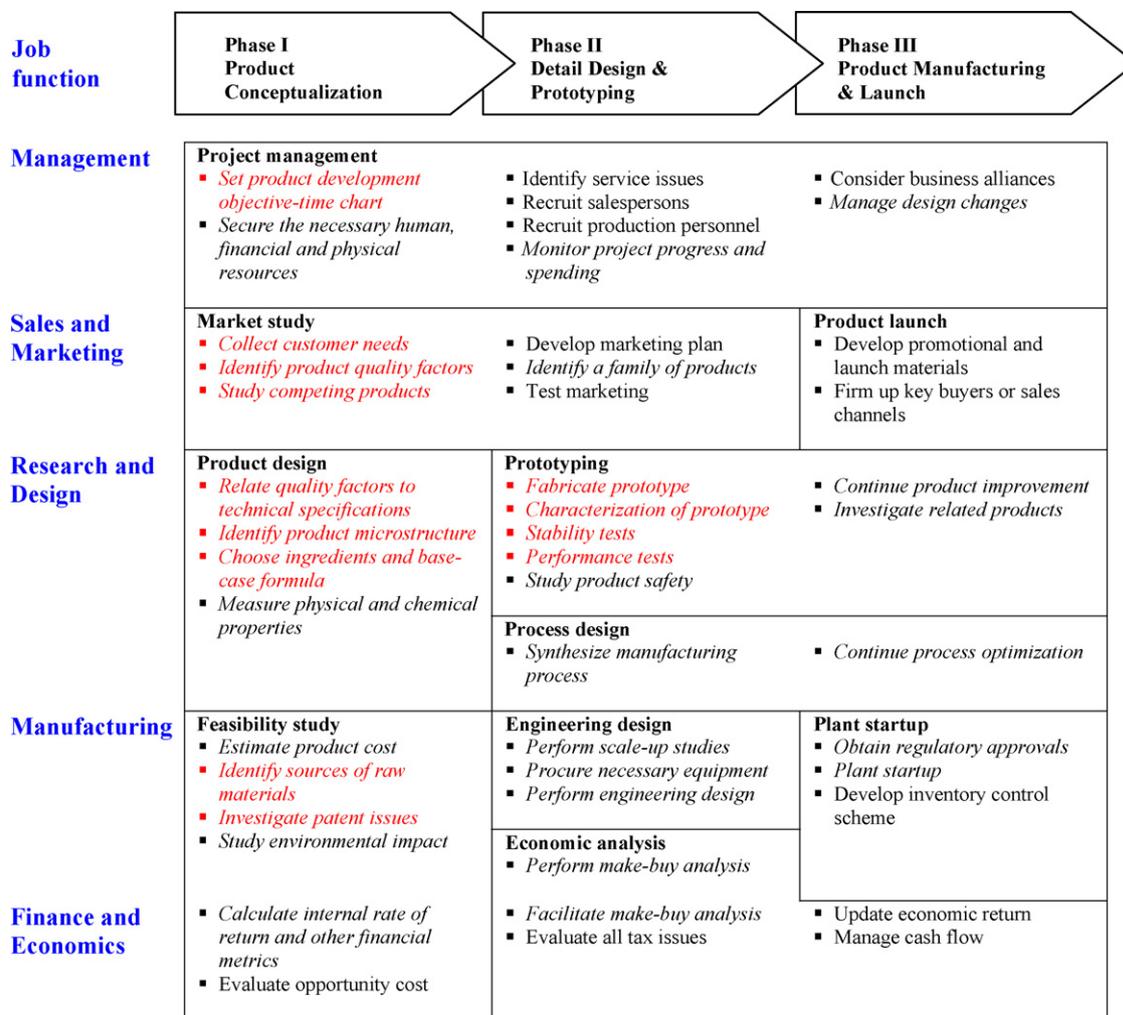


Fig. 1. Classification of product development activities by phase and by task.

uct with the desired performance. However, the proposed product development procedure has not been demonstrated by developing an actual product. In this study, we will expand this previous effort by collaborating with an industrial partner.

This article has two objectives. First, it attempts to put the various tasks for product development in proper perspective. The ways in which market demands are identified, product performance is evaluated and product reliability is tested have not received sufficient attention in the literature. Second, it illustrates the significance of integrating experiments, modeling, and synthesis for the development of a skin-care cream product. Despite the advances in engineering sciences, experimentation is crucial for the design of chemical products particularly those with an internal microstructure.

Although this integrative approach strives to offer a holistic view of product development, it is not necessary to cover all the relevant topics. Thus, we will focus on the italicized issues in red in Fig. 1. The discussion will be organized as follows. We begin with a general discussion of the elements of the integrative approach. This will be followed by discussions on the relevant unit tasks: project management, market study, product design, feasibility study, and prototyping. The skin-care cream case study will be dispersed throughout the general discussion. The traditional chemical engineering issues in Fig. 1 such as scale-up studies and plant startup are not discussed. Also,

some of the details related to the performance and stability of the specific skin-care cream under consideration are omitted as this commercial information is not central to the aim of this article.

## 2. An integrative approach

The starting point of a product development project is to formulate an **Objective-Time Chart** (Fig. 2) (Ng, 2004). This is part of the project management task in Phase I. It shows the objectives and subobjectives that have to be met in a given time horizon. For example, Objective D can be decomposed into subobjectives D1–D6. Subobjective D6 is further decomposed into D61–D65 and so on. This exercise is often used by a product/process development team to show all the team members the tasks that need to be performed and the time by which they should be completed. By offering a hierarchical view of the development project in its totality, every member knows what other members are doing to achieve the overall goal. Also, it highlights the tasks that can be carried out concurrently, thereby reducing the overall development time.

Also shown in Fig. 2 is the **RAT<sup>2</sup>IO Module** that we specify for each objective or subobjective. The acronym stands for resources, activities, time, tools, input/output information, and objective. Thus, we identify in advance the *resources* (money and

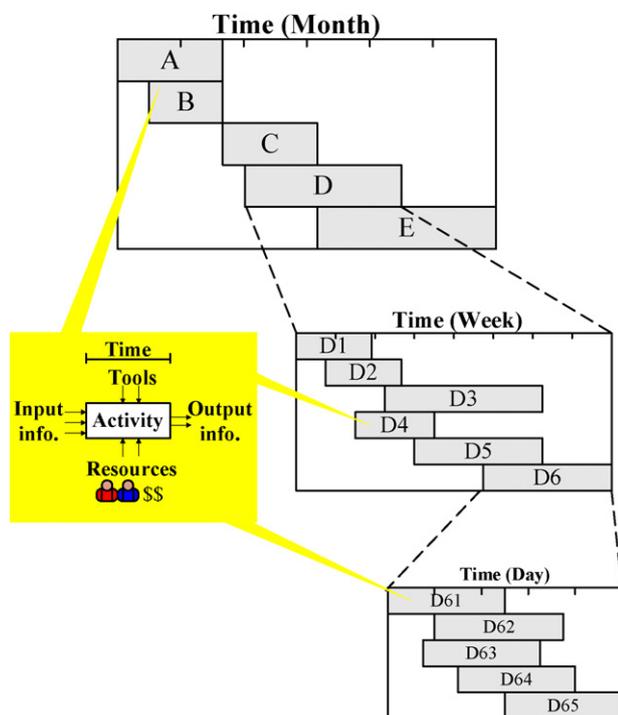


Fig. 2. A generic objective-time chart.

people) required to complete certain *activities* (experiments, modeling and synthesis) within a specified period of *time* using proper *tools* (experimental setup or software) to generate the necessary *information* and to meet the given *objective*.

The development of a consumer product such as a skin-care cream has been largely based on experience alone. While previous experience provides a good starting point, a substantial amount of experimental trial and error is often involved in the development of a new product. We submit that the product be synthesized by defining its constituents and microstructure, rather than simply screening different alternatives generated in a combinatorial manner. In doing so, understanding of the physical phenomena that control the product performance forms the basis for rationalizing the development process. Various models are utilized to describe the relationships among product performance, material properties, and product attributes, so as to establish a link between the targeted performance and the required technical specifications of the product. Experiments are used to support the modeling effort, as complete scientific elucidation of the underlying physical phenomena behind the technology of many chemical products is still a long way off (Wintermantel, 1999). Thus, this integrative approach does not eliminate the need for previous experiences. Rather, it helps to organize them in a systematic way so that they can be better utilized in the development of a new product.

Fig. 3 shows a generic **Workflow Diagram** for product development which underscores the importance of iterations. It shows three iteration loops. The inner loop illustrates how the ingredients and processing conditions are modified to yield the desired product performance. This is achieved by using a combination of experiments, modeling and synthesis. The outer loop shows that the product quality factors are redefined after evaluation of a product prototype by a test panel. Sometimes, test marketing is carried out after small-scale manufacturing. The outermost loop (dotted line) represents the situation where market needs are re-examined after market testing.

### 3. Project management

The deceptively simple objective-time chart is what distinguishes an expert from a novice. An effective project manager with the right experience can draw up a realistic timeline, ensure the availability of the necessary manpower and financial resources, and follow through to facilitate the flow of input/output information from one subobjective to another. Thus, this manager should have a good appreciation of all the RAT<sup>2</sup>IO modules in a product development project although no one is expected to master all the details in every module.

#### 3.1. Case study—skin-care cream

The target of this case study is a skin-care cream with new and improved functionalities. Based on the collective experience of all the team members, an objective-time chart (Fig. 4) and the RAT<sup>2</sup>IO module for the overall product development project (Table 1) were prepared.

### 4. Market study

The decision for developing a product may be technology-push or demand-led. For the former, a product concept can be stimulated by the discovery of an ingredient which gives some new or improved function. As an example, hyaluronic acid is now a key ingredient in a number of products because of its moisturizing function. Examples for the latter include antiseptic hand cleansing gel and nano-silver mask that are now readily available after the outbreak of the SARS (Severe Acute Respiratory Syndrome) epidemic in 2003.

Irrespective of the driver for product development, as part of marketing, the engineers and scientists are often part of a team to form an image of the product and to define its functions to meet anticipated or existing market needs. This information can be collected from frontline salespersons, advertising agents and customers. Typical considerations include:

#### Market situation

- Is the product technology-push or demand-led?
- Who are the target consumers for the conceived product?
- Who are the competitors?
- Does the demand for the product depend on season?
- What is the market size of the candidate product?

#### Productization

- What is the product image?
- What packaging would be the most practical for the desired application?

#### Company tradition and capability

- Does the product fit in the company's product lines?
- Can the company's technical strengths ensure product qualities?
- Are the sales channels in place to effectively market the product?

Clearly, product conceptualization requires a combination of technical know-how and marketing experience. Often, it is easier for chemical engineers to pick up marketing knowledge on the job than for business personnel to acquire the technical skills.

#### 4.1. Case study—skin-care cream

The antioxidant network of the skin is primarily localized in the epidermis and to a certain extent in the dermis. It is comprised of a variety of antioxidants, such as glutathione (GSH) and  $\alpha$ -tocopherol ( $\alpha$ -TOC), that protect skin against damaging effects from

**Table 1**  
RAT<sup>2</sup>IO module for the overall product development project.

Objectives	Input information	Activities	Tools	Resources	Time (month)	Output information
1. Project management	Business goal	Set objective time chart Keep checking project progress	–	Project managers Team leaders	0.5	Objective time chart
2. Market survey	Business goal Technology-driven functions of product	Collect customer needs Analysis survey results Identify a family of products	Questionnaire	Marketing and sales team	1.5	Customer wants Target range of customers Preliminary price range Product image and selling points
3. Product conceptualization	Customer wants  Product image and selling points	Identify product quality factors  Relate quality factors to technical specifications Identify product microstructure	Modeling	Formulators  Process engineers	1	Technical specifications/ product attributes Product microstructure
4. Design product formula	Technical specifications  Product microstructure Selection guidelines for supporting materials Heuristics for formula modification Government regulations on prohibited materials	Measure physical and chemical properties of active ingredients Choose supporting materials Design base case formula  Iterative formula modification Carry out performance tests	Instruments and techniques  Testing equipment	Technicians  Formulators Process engineers	6.5	Physical and chemical properties of active ingredients Prototype formula with refined concentration of active ingredients
5. Manufacturing planning	Prototype formula and fabrication procedure Government regulations on safety and environmental protection	Material sourcing  Synthesize manufacturing process Engineering design Estimate production cost Study environmental impact Investigate patent issues	Process synthesis procedure  Equipment models	Environmental engineers  Merchandizing network Process engineers Patent lawyers	5	List of suppliers and cost of raw materials Waste treatment planning Manufacturing process alternatives Potential patent opportunities
6. Financial analysis	Equipment costs Raw material costs Process alternatives	Capital budgeting Cost evaluation	Computation tools	Financial controller Engineers	3	Operating cost Capital cost Product selling price Financial return
7. Market testing (optional)	Prototype formula Prototype fabrication procedure  Existing marketing network	Carry out pilot scale production Distribute testing samples to potential buyers Develop marketing plan	Pilot scale facilities	Production team Marketing and sales team	3	Key buyers and sales channels Feedbacks for refining formula

## Workflow for Product Development

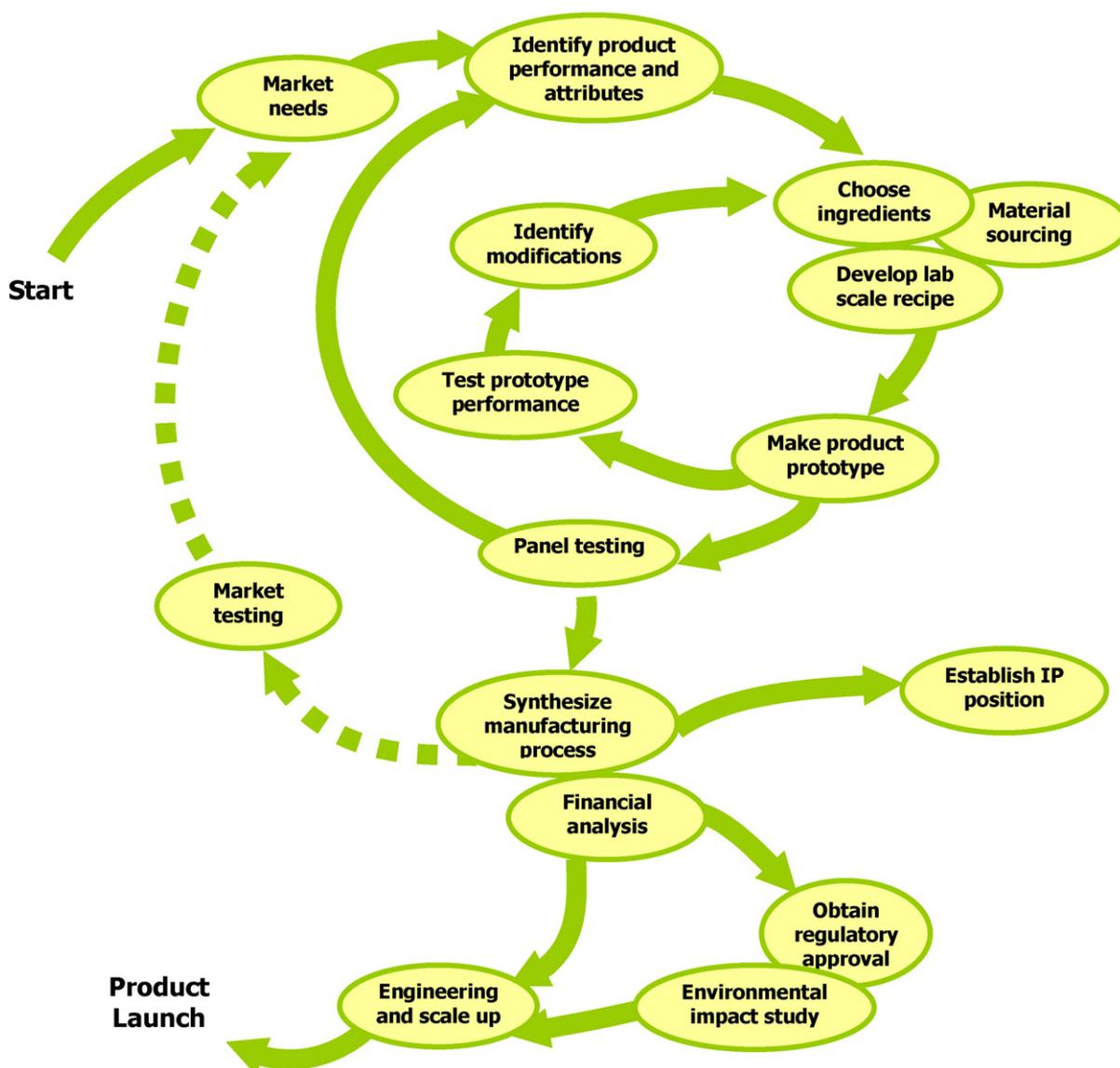


Fig. 3. A generic workflow diagram for product development.

reactive oxygen species (ROS). It is now well established that solar UV radiation can stimulate ROS production in skin cells and skin tissue (Hanson, Gratton, & Barden, 2006; Heck, Vetrano, Mariano, & Laskin, 2003), causing a dramatic decrease in such antioxidants due to the oxidative injury by these UV-induced free radicals. Also, ROS stimulate the synthesis of collagen-degrading enzymes known as matrix metalloproteinases. Loss of collagen, one of the primary structural components of dermis responsible for conferring strength and support to human skin, will lead to the appearance of wrinkles (Craven et al., 1997). Given the causal role of ROS in skin aging and in the development of skin cancer (Baumann, 2007), in addition to blocking the UV light, the supplementation of sunscreen with antioxidants represents a rational approach to ameliorating the solar UV-induced skin damage (Farris, 2005; Thiele, Hsieh, & Ekanayake-Mudiyanselage, 2005; Weber et al., 1997).

This was achieved by developing a skin-care cream with two new ingredients, zinc oxide nanoparticles and an herbal extract. Zinc oxide is well accepted as a physical UV absorbent and has been widely used in sun-screening products. In this investigation,

an antioxidant derived from *Fructus Schisandrae* (FS) was used due to its proven antioxidant function (Ko & Mak, 2004). In addition, moisturizing function is also required.

### 4.1.1. Collecting customer needs

Some of the questions the business manager/engineer/formulator used to define the product are listed below:

- Should the product be a facial or body product?
- Should the product be a cream or lotion?
- Should the product be adjusted depending on season?
- Should the container be a tube, a glass jar or a bottle with a pump head?
- Can other functions be included to make the product more attractive?

To shed light on the questions above, the following information/ideas/comments in the same order as the questions were collected from both frontline salespersons and engineers:

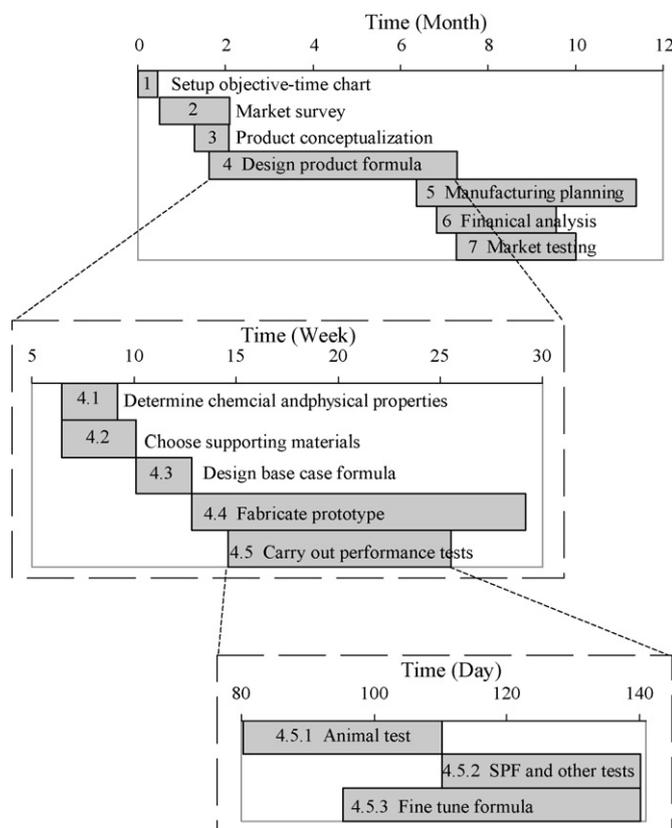


Fig. 4. Objective-time chart of the skin-care cream development project.

- The quality requirements and, therefore, the formulas for these two products are actually different. The consumer usually demands a higher quality product for the face than for the body.
- A lotion which spreads readily is more suitable for outdoors, a larger area such as the leg or body, whereas a cream is right for a smaller area such as the hand or face.
- The majority of people accept the need to apply sun-screening products. However, sunscreen cream is perceived to be thick and greasy. They are used only in summer time during outdoor activities.
- Since most consumers do not like a greasy feeling, a lotion or a light cream is preferred.
- Since UVA (320–400 nm) can pass through glass (Baumann, 2007), daily application of a sun-screening product with a moderate sun protection factor (SPF) value can be recommended for use indoors.
- There is a higher demand for sun-blocking and whitening products in summer time. Products resisting dryness are usually in higher demand in winter and dry weather.
- In the market, it is not difficult to find a day cream containing a moderate SPF value of 8–15 which can be used daily for all seasons.
- It is rather difficult to retrieve the lotion at the bottom of a bottle with a pump head.
- As recommended by an advertising agency, a bottle size of 50–100 mL is appropriate for a day cream.
- Selling through chain retail stores can be arranged.
- A retail price in the range of HK\$150–350 per bottle should be considered.
- Unlike other products, our product with an herbal antioxidant offers a unique selling point.

- Strong scientific evidence that the herbal extract neutralizes UV-induced free radicals is needed.
- Hyaluronic acid can be considered as a moisturizing agent. However, enhancers might be needed to promote its penetration into the skin (Rieger, 1998).
- Natural products are preferred to artificial ingredients. Mosquito repellent can be added to the sunscreen to form a multifunctional product.
- After launching the first product, a series of related products derived from the first product can follow.

#### 4.1.2. Identifying product quality factors

After a number of brainstorming sessions, it was decided that the product should be a light facial day cream with sun-screening, antioxidant and moisturizing functions. It would be an all-season product. The sun-screening ingredient should provide a natural look. This ruled out the use of microsized ZnO particles which reflect visible light and lead to whitening. From a sensorial point of view, improved spreadability and a less greasy feel was targeted.

#### 4.1.3. Studying competing products

Intellectual property (IP) position is an important consideration for a company to commit considerable resources to launch a new product in the market. Skin care is a vast market with hundreds of different products. Table 2 shows the results of a patent search of six worldwide cosmetic companies on skin care applications, particularly those related to nanotechnology. Obviously, L'Oréal is the largest patent holder. Its "De-crease series" involves collagen biospheres that can penetrate into the skin and expand nine times of their volume when in contact with water in the skin to soften the expression lines (L'Oréal, 2008). Shiseido developed the "O/W/O emulsification" technology in which superfine oil droplets are contained within water droplets in oil (Yoshida et al., 1999). It allows two incompatible oils being used in the same formula. There are also products with vitamin E as an antioxidant on the market. However, it was decided that our day cream would be more suitable for our target customers.

## 5. Product design

Research and design tasks are performed in parallel with, rather than subsequent to, sales and marketing tasks. The objective is to translate the desirable quality factors identified by the marketing team into technical specifications, including the active and supporting ingredients to be included in the product as well as the structure of the product itself. A base-case recipe would be developed during this phase. During this process, the potential technical challenges and opportunities in making the product are identified; this information should be provided to the marketing team as product conceptualization is often a compromise between desirability and practicality.

Naturally, ingredients are selected based on their capability for performing a certain function. For products driven by the discovery of a functional ingredient, the active ingredient(s) are already fixed and the focus is on specifying the appropriate supporting ingredients such that the product possesses additional quality factors as desired by potential consumers. For demand-led products, the R&D activities begin with finding the suitable active ingredient(s). The chemistry knowledge provides a good starting point to identify potential candidates. In some cases, new molecules can be identified as the most feasible candidates based on chemistry insights. The candidates are then screened to identify a handful of lead compounds to be further investigated to verify their capability and to come up with the best choice. High-throughput screening

**Table 2**

Number of patents for six worldwide cosmetic companies in skin care and sun-screening and protection applications, without and with using nanotechnology.

Company	Number of patents			
	Skin care applications	Nanotechnology involved in skin care applications	Sun-screening and protection applications	Nanotechnology involved in sun-screening and protection applications
Avon	9	0	6	0
Kanebo	314	0	0	0
Kao	428	25	0	0
L'Oreal	686	17	367	33
P&G	82	0	23	0
Revlon	0	0	5	0
Shiseido	583	4	171	0

techniques, which are capable of quickly testing a large number of samples for a particular response, are valuable tools to expedite such a search.

As an alternative to the experiment-based trial and error approach, model-based search techniques such as computer-aided molecular design and computer-aided molecular/blend design have been developed (Achenie, Gani, & Venkatasubramanian, 2003; Gani, 2004b). Starting from the specifications of the desired product, molecular structures or mixtures that satisfy the target can be found with the help of mathematical models for estimating the desired properties. In reality, the majority of chemical-based consumer product design problems are solved using a combination of experiment-based and model-based techniques, because validated mathematical models are not available for all desired properties and/or product performance evaluations. Model-based search techniques serve as valuable tools for identifying a small number of compound structures which possess the desirable properties, thereby greatly reducing the search space that has to be investigated experimentally using a trial and error approach.

The development of multifunctional products poses additional challenges such as the need to combine incompatible ingredients in a single delivery system. Supporting ingredients are normally chosen among commonly used materials, which for personal care products may have to be approved by the regulatory authorities. These supporting ingredients are often chosen based on previous

experience with similar products, although such a choice can eventually be justified on scientific grounds.

In Phase I, the marketing plan and the product attributes may constantly change. As a consequence, the R&D plan has to be revised accordingly. For example, an extra active ingredient may need to be incorporated to achieve an additional quality factor because of a newly identified market demand. The engineer/chemist may have to look for a new ingredient and consider its compatibility with the existing ingredients.

### 5.1. Case study—skin-care cream

#### 5.1.1. Relating quality factors to technical specifications

The target product was a day cream with sun-blocking, antioxidant and moisturizing functions. Two active ingredients, namely *Fructus Schisandrae* extract and zinc oxide nanoparticles, distinguish the product from its competition. In addition, the product has to possess additional rheological, sensorial and physical quality factors that are typical to a facial cream, which can be related to the ingredients, certain product attributes or technical specifications as indicated in Table 3. These targets for the day cream were decided based on the collective experience of the development team. For the moisturizing function, a humectant or emollient can be added. Glycerol, propylene glycol and hyaluronic acid are commonly used for this purpose. For a product to spread readily,

**Table 3**

Quality factors, the corresponding ingredients, product attributes and technical specifications, and performance tests.

Quality factors	Ingredients, product attributes and technical specifications	Performance tests
<i>Functional</i>		
Sun-screening effect	A sun protection factor (SPF) value of 8–15 is targeted for a daily facial cream ZnO nanoparticles are used as a sun-screening agent	Measurement of SPF values
Antioxidant effect	An herbal extract with antioxidant function is used	Animal test
Moisturizing effect	Humectants and moisturizing agents are used	Skin surface hydration content, transepidermal water loss (TEWL), etc.
<i>Rheological</i>		
Good spreadability	A low viscosity (6,000–50,000 mPa s) is preferable	Assessment by a test panel Viscosity measurement
<i>Sensorial</i>		
Non-greasy	Oil content should be low O/W emulsion is preferred	Assessment by a test panel
Non-irritating	Mild ingredients are used	Assessment by a test panel
Soft feel	Emulsion droplet size should be minimized Emollients are used	Assessment by a test panel
<i>Physical</i>		
Long shelf life	Good stability must be achieved	Stability tests (freeze/thaw cycles)
Non-whitening appearance	ZnO nanoparticles are used instead of microparticles	PSD analysis for ZnO nanoparticles

**Table 4**  
Examples of excipients and the corresponding selection criteria.

Excipients	Examples	Suggested concentration (wt%)	Selection criteria and considerations
Emollient [required HLB value]	<i>Synthetic oils</i> : caprylic/capric triglyceride [5], C <sub>12</sub> –C <sub>15</sub> alkyl benzoate [13] <i>Natural oils</i> : sunflower oil [7], sweet almond oil [7], coconut oil [8]  <i>Silicone oils</i> : cyclomethicone [5], dimethicone [5] <i>Fatty alcohols</i> : cetyl alcohol [15.5], cetearyl alcohol [15.5]	10–40	Natural oils are usually more acceptable by the customers  Silicone oils are non-sticky and with high spreadability. Its water repellent property is good for waterproof sun-blocking products Use fatty alcohol, polyol esters or fatty acids as co-emulsifiers (Spiess, 1996) at a concentration below 2% to avoid soaping
Humectant	Glycerol, propylene glycol, butylene glycol, sorbitol	1–5	Materials with low freezing point are preferable.
Thickener	Carbomers, xanthan gum, carboxymethyl cellulose, acrylates/C10–30 alkyl acrylate crosspolymer [polymeric emulsifier]	0.1–0.5	Carbomers also act as stabilizer in an O/W emulsion, but they have low compatibility with electrolytes and should be neutralized with alkaline to increase viscosity. It shows thickening function in pH values of 5–9 (Lubrizon Advanced Materials, Inc., 2002) Neutral thickeners should be considered for pH sensitive system
Emulsifier [HLB value]	Steareth-2 [4.9], oleth-20 [15], glyceryl stearate [3.8], PEG-100 stearate [16], polysorbate 20 [16.7]	1–6	Cationic emulsifiers are usually more irritating than anionic emulsifiers Anionic emulsifiers are sensitive to low pH and electrolytes Non-ionic emulsifiers are widely used in skin care products, HLB system only applies this type of emulsifiers A mixture of emulsifiers with high and low HLB values gives better stability results than a single emulsifier with the exact required HLB value
Film former	PVP/dimethylaminoethylmethacrylate copolymer, PVP/hexadecene copolymer, aloe vera	0.1–2.5	Film formers can increase film thickness and water resistance, but also leaves a sticky feel
Stabilizer	Sodium chloride, EDTA disodium salt dihydrate	0.01–0.2	–
Neutralizer	Triethanolamine (TEA), citric acid	0.01–0.5	Follow manufacturers' recommendations.
Preservative	BHT, tocopheryl, diazolidinyl urea, iodopropynyl butylcarbamate, methylparaben, propylparaben	0.01–0.5	–

based on our own experience, a lotion or light cream with a viscosity between 6000 and 50,000 mPa s may give a more pleasant feel. The desired sensorial quality factors such as non-greasiness and softness are achievable by adjusting the emollient content, the ingredients and constituent droplet size. Furthermore, the use of appropriate emulsifiers with proper concentrations is critical to the stability of the product. The presence of zinc oxide particles in the formula can lead to whitening effect on the skin due to the reflection of visible light. This problem can be avoided by using zinc oxide nanoparticles.

### 5.1.2. Identifying the product microstructure

The day cream can be selected to be an oil-in-water (O/W), water-in-oil (W/O), or double (W/O/W or O/W/O) emulsion. Such a selection of product delivery vehicle should be driven by both practical considerations and consumer perception. A W/O emulsion is preferable from the dermatological point of view, since the lipid film on the skin favors oil-soluble active ingredients. An O/W emulsion is more appreciated by the consumer due to its less greasy feeling (Spiess, 1996). In the end, the customers' perception was deemed to be more important, and an O/W emulsion was chosen.

### 5.1.3. Choosing ingredients and base case formula

To come up with a base case formula, we have to decide on the key ingredients and their concentrations. In addition, supporting ingredients such as emollients, humectants, thickeners, stabilizers, emulsifiers, preservatives, and fragrances are also selected to meet the technical specifications. Table 4 lists some examples of commonly used supporting ingredients, along with their recommended concentrations and selection criteria. However, choosing among 15,000 commercially available materials is a daunting task (Ash & Ash, 1994; Flick, 1991). Therefore, it is a common practice for expe-

rienced formulators or chemists to compile their own short list. The choice is also affected by other factors such as the availability in the market, regulatory control, and the cost of the materials.

Table 5 shows the base case formula (prototype 1) as well as prototypes 2 and 3 in subsequent iterations. Note that some of the chemicals go by their trade names. The zinc oxide nanoparticles obtained from Advanced Nanotechnology Ltd. (ZinClear-S\_60CCT and ZinClear-S\_60AB) were suspended in caprylic/capric triglyceride and alkylbenzoate, respectively. Both samples contain 60% of zinc oxide nanoparticles. The Fructus Schisandrae extract was produced in our own laboratory (Luk, Ko, & Ng, 2008a, 2008b). These two key ingredients were mixed into the oil phase of the base case formula.

Among the major concerns for selecting emollients are the product's greasiness, softness and stickiness upon application. Since market survey indicated that customers favor natural ingredients, sunflower oil (Sigma) and sweet almond oil (Sigma-Aldrich) were selected for this product. A silicon oil, dimethicone, was chosen due to its non-sticky, highly spreadable, and water repellent properties. Taking into account the oil contents in the zinc oxide suspension mixture, 1% sunflower oil, 1% almond oil and 2% silicon oil were used in the base case formula. The concentration of cetyl alcohol, a co-emulsifier, was kept at 1%. Note that a cream containing more than 2% cetyl alcohol might result in soaping effect. In addition, 0.2% of polyvinyl pyrrolidone (PVP)/dimethylaminoethylmethacrylate copolymer was used as a film former to promote the formation of a uniform sunscreen film on the skin upon applying the product in prototype 1. Carbomers (Carbopol® 940, 941, Lubrizon) and xanthan gum (Sigma-Aldrich) were selected as thickeners, again on the basis of common usage. Glycerol (Sigma-Aldrich) and propylene glycol (Acros) were chosen as humectants. Ethylenediaminetetraacetic acid disodium salt dihydrate (Invitrogen) and a

**Table 5**

Formula of the skin-care cream with sun-screening, antioxidant and moisturizing functions.

	HLB value	Ingredient type	Prototype 1 (wt%)	Prototype 2 (wt%)	Prototype 3 (wt%)
<b>Oil phase</b>					
Zinclear-S.60CCT	5	Sun-blocking agent	4	4	4
Zinclear-S.60AB	13	Sun-blocking agent	12	12	12
C <sub>12</sub> –C <sub>15</sub> alkyl benzonate	13	Emollient	1	2	2
Sunflower oil	7	Emollient	1	0.5	0.5
Sweet almond oil	7	Emollient	1	0.5	0.5
Cetyl alcohol	15.5	Co-emulsifier/opacifier	1	1.5	1.5
Dimethicone	4	Emollient	2	2	2
Cocoa butter	11.5	Emollient	–	1	2
Polysorbate 20	16.7	Emulsifier	–	0.16	0.82
GMS 165 (PEG-100 stearate and Glyceryl stearate)	11	Emulsifier	–	4.84	4
Stearth-2	4.9	Emulsifier	2.5	–	0.18
Oleth-20	15	Emulsifier	2.5	–	–
Fructus Schisandrae extract	–	Anti-oxidant	2	2	2
PVP/dimethylaminoethylmethacrylate copolymer	–	Film former	0.2	–	–
<b>Aqueous phase</b>					
Carbopol® 940	–	Thickener	0.14	0.35	0.35
Xanthan gum	–	Thickener	–	–	0.2
Glycerol	–	Humectant	3	3	3
Propylene glycol	–	Humectant	2	2	2
Hyaluronic acid (1 wt% in H <sub>2</sub> O)	–	Moisturizing agent/humectant	1	–	–
EDTA disodium salt dihydrate	–	Stabilizer	0.2	0.1	0.1
Triethanolamine	–	Neutralizer	0.1	0.1	0.2
Water	–	–	Balance	Balance	Balance
<b>Preservative phase</b>					
Liquid Germall® Plus	–	Preservatives	0.7	0.7	0.7

mixture of diazolidinyl urea and iodopropynyl butylcarbamate (Liquid Germall® Plus) were used as the stabilizer and preservatives, respectively. Their compositions were selected based on the suggested concentrations in Table 4. Fragrance was not considered in this formula.

The next step was to determine the usage of emulsifiers. In theory, emulsifiers should be selected based on the required hydrophilic–lipophilic balance (HLB) value, which can be calculated based on the overall HLB value of the oil mixture,

$$HLB_{\text{required}} = \sum HLB_i \times x_i \quad (1)$$

where  $HLB_i$  and  $x_i$  refer to the HLB value and the weight fraction of the oil component  $i$ . The HLB values of some common emollients and emulsifiers can be found from the catalogs provided by the suppliers and from literature. Some of these values are listed in Tables 4 and 5. Alternatively, the HLB values of different emulsifiers could be calculated based on their particular functional groups (Vaughan & Rice, 1990). However, the HLB system does not provide a definite answer to the selection problem, as other properties such as the compatibility of ingredients, the viscosity of the continuous phase and size of the emulsion droplets could affect the rate of creaming or phase splitting (Lissant, 1974), which dictates the stability of the emulsion system. Therefore, experienced formulators normally select an appropriate mixture of emulsifiers according to the types of emollients used. Experimentally, the required HLB value can be determined by mixing a pair of emulsifiers with high and low HLB values with the desired sample and see which HLB value yields a stable emulsion (Courtney, 1997; Uniqema Ltd., 2005).

The HLB values of Fructus Schisandrae extract and PVP/dimethylaminoethylmethacrylate copolymer were not known. It was decided that they could be ignored at this stage assuming that their contribution to the overall required HLB was not dominant. For this formula, the overall required HLB was calculated to be 9.9 using Eq. (1). In general, a mixture of two emulsifiers with high and low HLB values would give better stability than a single emulsifier having the same HLB value. For example, stearth-2 and oleth-20, with HLB val-

ues of 4.9 and 15, respectively, can be mixed to match the required HLB value of 9.9 for the oil mixture. For prototype 1, a total of 5 wt% emulsifiers, 2.5% stearth-2 and 2.5% of oleth-20, was used.

## 6. Feasibility study

The objective here is to obtain a preliminary assessment of the manufacturing issues related to the perceived product, in order to judge the economic and operational feasibility of the manufacturing process. A procedure and heuristics for generating the process alternatives for making creams and pastes were discussed by Wibowo and Ng (2001). Process alternatives for generating the desired microstructure should be identified. This will help provide an estimate of the product cost, and thus the selling price. Often, this is decided by a balance between an acceptable return on investment and the selling price of the products on the market. For a given production rate, material and energy balance analyses are performed to determine raw material consumption, waste generation, utility consumption, and the required processing time. The cost of raw materials, especially the active ingredients, often represents a major portion of the product cost. In addition to transportation costs, import and export taxes and advertising costs must be considered as they often substantially affect the overall economics. Often, a trade-off exists between raw material cost and production cost, as lower purity raw materials may require expensive pre-treatment before it can be incorporated into the product. Some impurities are totally unacceptable. For example, the presence of heavy metals in a skin-care product, even at a very minute concentration, can lead to a disastrous product recall. Therefore, it is crucial to identify the raw material source. Availability and consistency of the supply of the raw materials, especially the natural herbs, should also be considered at this stage.

There is no alternative to environmental compliance. Although the base case recipe and the process plant are not very exact at this point, local environmental regulations should be consulted to check if there is any limit on the disposal of certain waste materials

and whether such limits may lead to the need for expensive waste treatment facilities.

This is also the right time to consider whether to file a patent to secure an IP position for the product. For example, a patent can be filed for the skin-care cream formula. Since the composition has not been fixed, a wider range of compositions should be claimed to provide adequate protection. Because the manufacturing process tends to be generic for a particular type of products say creams and pastes, a process patent may not be of a high value unless the process involves a novel technology for making the product under consideration. In particular, technology for producing a key ingredient in the product may provide the company with a competitive advantage.

## 6.1. Case study—skin-care cream

### 6.1.1. Identifying sources of raw materials

Except for Fructus Schisandrae extract and possibly ZnO nanoparticles, all raw materials will be sourced around the world based on availability, quality and price. The main active ingredient, Fructus Schisandrae extract, is not available in the open market. For this reason, it will be manufactured on our own. Instead of starting with the fruits, an extract prepared by supercritical CO<sub>2</sub> extraction can be purchased in Mainland China. This will be further processed to obtain the desirable fraction. A new process has been developed for manufacturing nano ZnO via a one-step mechanochemical method by milling zinc sulfate heptahydrate and potassium hydroxide, with potassium chloride serving as the matrix salt (Lu, Ng, & Yang, 2008). This reaction has economic potential for manufacturing high-quality ZnO nanoparticles.

### 6.1.2. Considering patent issues

Filing a patent for the optimized cream formula containing the ingredients is planned. Non-provisional patents have been filed for a process to obtain highly pure Schisandrin B and (–)Schisandrin B, a diastereoisomer, from Fructus Schisandrae using a series of extraction, chromatography, and crystallization steps. Thus, our product will be protected to some degree.

## 7. Prototyping

The prototyping activities focus on bench-scale experiments to make a prototype of the conceived product in order to test the product performance. The base case recipe identified in product design (Phase I) is used as a starting point for the first prototype, which is then subjected to a series of performance tests and iterations to come up with a product with the desired performance. All required tests and the amount of sample needed for each test should be identified, so that a sufficient amount of each prototype material can be prepared in advance.

Mixing sequence and technique in making a skin-care cream can have a significant impact on emulsion properties such as droplet size distribution, which affects the sensorial quality factors and stability of the product. Table 6 summarizes the general heuristics for mixing sequence and technique. While most of the heuristics are based on common practices, they can be derived from the basic knowledge of the underlying phenomena of emulsion formation.

Detail design and prototyping is inevitably an iterative process. Depending on the product characterization and performance test results, the product formula has to be revised. Physicochemical insights and previous experience are used to guide the iteration process. Table 7 offers some guidelines for adjusting the recipe based on the test results. In making creams, it is important to understand how various ingredients, their composition, and the product microstructure affect the performance of the product. For example,

**Table 6**

Heuristics for mixing sequence and mixing techniques.

<p><i>Mixing sequence</i></p> <p>Prepare aqueous phase and oil phase separately prior to mixing the two phases. To make O/W emulsion, add oil phase into water phase. To make W/O emulsion, add aqueous phase in oil phase. O/W emulsion can also be obtained from W/O emulsion by cooling the emulsion below its thermal phase inversion temperature (PIT) (Lehnert, Tarabishi, &amp; Leuenberger, 1994).</p> <p>Preservatives are usually added to the continuous phase after the emulsion is formed. If solids preservatives are used, they should be mixed in oil phase. Color pigment, pH adjusting components, and heat-sensitive ingredients such as fragrances and perfumes, should be added at lower temperature after the emulsion is formed.</p> <p><i>Preparation of aqueous phase</i></p> <p>Carbomer (synthetic polymer of acrylic acid) and xanthan gum thickeners should be pre-dissolved with part of the water used in the formula.</p> <p><i>Preparation of oil phase</i></p> <p>Solids emollients should be slowly melted with liquid emollient ingredients using gentle heating. The emulsifiers should be added as the last part of oil phase. The actual concentration of emulsifiers should be adjusted based on the actual HLB value.</p> <p><i>Mixing/homogenization technique</i></p> <p>It is recommended to use a homogenizer/mixer with adjustable stirring speed for bench scale experiment, and to keep the same stirring speed as that in the production scale. Keep the stirring speed of mixer or high-shear homogenizer below 10,000 rpm to avoid breaking down the carbon chains of the thickener by the strong mechanical energy. If phase inversion method is used, vigorous stirring is not necessary. In industrial practice, the homogenizer should be equipped with vacuum line to remove bubble during agitation. In bench scale experiment, bubbles could be removed in vacuum oven or sonication bath.</p>
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product viscosity can be increased by using a higher concentration of thickener, while a smoother feel on the skin may be achieved by adjusting the oil to water phase ratio, using a different emollient, and so on. The modified recipe is then used for making the next prototype.

Typically, a number of standard performance tests are available for a specific class of products. For example, tests for hair conditioners include assessing the condition of real human hair after applying the conditioner. For a sunscreen cream, the skin protection factor is considered in a standard test. One should be aware of opposition from some quarters against using animals for product testing.

## 7.1. Case study—skin-care cream

### 7.1.1. Fabricating prototype

Each version of the prototype was inspected for its feel on applications, and stability. If the prototype failed the stability test, an improved version would be prepared based on heuristics and experience. A prototype that passed the preliminary inspections would undergo performance and stability tests. Further adjustments of the formula or fabrication procedure were made if the performance was not satisfactory. This iterative process continued until a satisfactory prototype was produced. For conciseness, the description below covers only three iterations although many more were actually made.

**7.1.1.1. Prototype 1.** The composition of prototype 1 is listed in Table 5. A 200-g cream sample was prepared in order to obtain a sufficient quantity for performing the various tests. The ingredients were separated into three groups and mixed separately. The oil phase contained all the oil-soluble ingredients, the aqueous phase consisted of the water-soluble ingredients and the third

**Table 7**  
General considerations on improving cream formulation based on test results.

Test results	Adjustments
Emulsion cannot form instantaneously	Adjust emulsifiers concentration Consider using different emulsifiers
Too viscous	Reduce thickener concentration Consider another thickener
Not viscous enough	Increase thickener concentration (for Carbomer, up to 0.5 wt%) Consider another thickener or a mixture of thickeners Consider employing emollients which are solids in nature at room temperature
Greasy	Reduce emollient concentration Change emollients
Not smooth enough	Reduce droplet size by increasing the stirring speed of homogenizer Improve mixing technique
Sticky	Reduce emollient concentration Reduce film former concentration Change emollients
Soaping/creaming	Replace part of emollient with silicon oil
pH too high	Add acidic pH controlling compound, such as citric acid
pH too low	Add alkaline pH controlling compound, such as triethanolamine (TEA)
Phase split after stability test	If oil phase splits out, reduce the HLB value of emulsifiers If aqueous phase splits out, increase the HLB value of emulsifiers When solids suspension is involved in the formula, consider using polymeric emulsifiers

group was the preservatives. The mixing procedure was developed based on the heuristics in Table 6. The aqueous phase was prepared first by dispersing the thickener, Carbopol® 940, in 80 g of water under mild heating and a stirring speed of 800 rpm using a magnetic stir plate. Most of the remaining components in the aqueous phase were mixed in a separate beaker and heated to 70 °C. These two solutions were combined at 70 °C after the thickener was completely dissolved. Triethanolamine, the pH modifier, was added last; the solution was thickened and the pH value reached 5–6. The oil phase was prepared by mixing cetyl alcohol, dimethicone, sunflower seed oil, and sweet almond oil under gentle heating. Zinc oxide suspension, Fructus Schisandrae extract, stearth-2 and oleth-20 were then added to the mixture sequentially. After raising the temperature of the oil phase to 70 °C, the oil phase was added to the aqueous phase slowly at a stirring speed of 1000 rpm. The mixture emulsified immediately and was left for natural cooling. The droplet size of the mixture was further reduced with the use of a hand-held mixer (Kenwood) for 3–5 min and then returned to moderate mixing, as excessive mixing might induce bubbles or weaken the thickeners. When the temperature of the emulsion reached 45 °C, the preservative phase was added with general mixing. The cream was then immersed in a sonication bath for 5 min to remove any trapped bubbles and was then allowed to cool to room temperature. According to the vendor of zinc oxide, the pH should not be kept below 7.5. Since the pH value for cosmetic products is usually limited to 5.5–8.0, we decided to maintain the pH value of this skin-care product close to 7.5 with the pH modifier.

#### 7.1.2. Characterization of prototype

Prototype 1 was examined visually on whether an emulsion was formed and its stability against phase split. It was also characterized in terms of viscosity, pH as well as the feel on applications (Table 8). The viscosity was measured by a viscometer (Brookfield DVII+ Pro) and the viscosity was found to be lower than the specification. The pH value was determined by a pH meter (Hanna Instruments, HI 9025). The average droplet size could be determined by viewing the emulsion droplets under a microscope and the particle size distribution

by a PSD analyzer (Coulter, LS 230). An average droplet size of 1.4 μm was determined. The emulsion gave acceptable softness and a non-greasy feel. However, it left a sticky feel after applying on the skin.

#### 7.1.3. Stability tests

Simple emulsion is thermodynamically unstable and is expected to eventually separate into oil and aqueous phases. For a day cream, a minimum lifetime of 3 years without phase split or significant changes in color and odor is required. Instead of waiting for 3 years before product launch, an in-house stability test procedure was followed. The prototype was subjected to low temperatures (–15 and 5 °C), elevated temperature (48 °C) for 3 months, freeze/thaw cycle, high humidity, and so on. Only the freeze/thaw cycle test is reported here. The sample had to pass through two to three freeze/thaw cycles, each with temperature swinging from 48 °C, to room temperature, to –15 °C and then back to room temperature, with a duration of 24 h at each temperature. The appearance, pH and viscosity were tested after each cycle. The results of these tests are summarized in Table 8. Phase separation occurred after the first freeze/thaw stability cycle for prototype 1.

**7.1.3.1. Prototype 2.** As shown in Table 5, the amount of film former was reduced to zero to avoid the sticky feel. The amount of Carbomer was increased to 0.35 wt% to improve the cream viscosity. To improve stability, the emulsifiers were replaced by Polysorbate 20 and GMS 165 (a mixture of glycerol stearate and PEG-100 stearate, emulsifiers with high and moderate HLB values, respectively). A solid emollient, cocoa butter, was added to obtain a final HLB value of 11.7.

Prototype 2 was produced using the same procedure described above and the results for characterization and stability tests are listed in Table 8. As for prototype 1, the emulsion formed immediately when the two phases were mixed. The cream softness and greasiness was acceptable. However, the viscosity was still far below the specification. The formula was still not very stable and a small amount of oil appeared after the first freeze/thaw cycle.

**Table 8**  
Characterization and stability tests for prototypes 1–3.

Items	Prototype 1		Prototype 2		Prototype 3	
	Results	Suggested changes	Results	Suggested changes	Results	Suggested changes
Emulsion formation	Successful	–	Successful	–	Successful	–
pH	7.5–8.0	–	7.5–8.0	–	7.5–8.0	–
Viscosity (cP)	2140 (Spindle #3, 10 rpm, 20 °C)	Increase amount of thickener to 0.4% Add solid emollients	5090 (Spindle #3, 10 rpm, 20 °C)	Increase amount of thickener Use mixture of thickeners Add xanthan gum to make the total concentration of thickener up to 0.55%	15200 (Spindle #3, 5 rpm, 20 °C)	Add in polymeric emulsifier
Average droplet size (μm)	1.40	–	–	–	–	–
Softness (not soft/ acceptable/very soft)	Acceptable	–	Acceptable	–	Acceptable	–
Greasiness (greasy/ acceptable/non-greasy)	Non-greasy	–	Acceptable	–	Non-greasy	–
Stickiness (non-sticky/ sticky/very-sticky)	Sticky	Reduce the amount of film former	Non-sticky	–	Non-sticky	–
Stability (stable/acceptable/ unstable/unacceptable)*	1st cycle: unacceptable (phase separation)	Change emulsifier: replace oleth-20 with polysorbate 20 and GMS 165	1st cycle: unstable (some phase separation)	Combine emulsifier with lower HLB value, such as steareth-2	1st cycle: acceptable; 2nd cycle: acceptable	Add in polymeric emulsifier to further improve stability

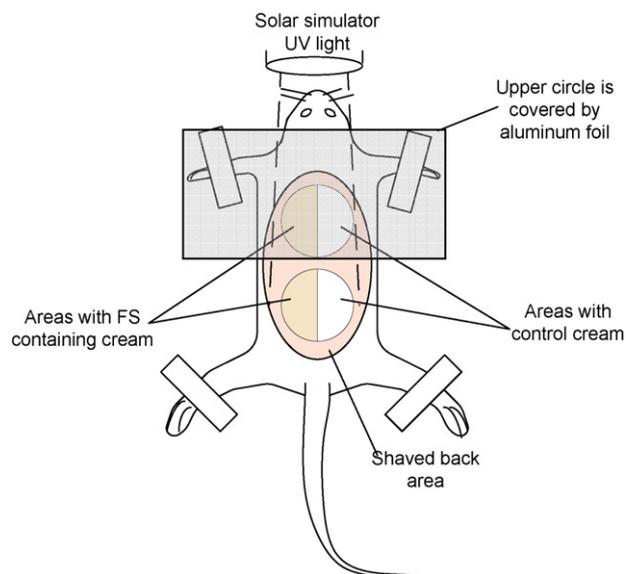
Note. \*: Tolerance of stability after one freeze/thaw cycle. Stable: change in viscosity < 10%, Acceptable: 10% < change in viscosity < 20%, Unstable: 20% < change of viscosity < 40%, Unacceptable: change of viscosity > 40%.

**7.1.3.2. Prototype 3.** To further increase the viscosity, xantham gum was used along with Carbopol® 940 for a total thickener concentration of 0.55 wt% (Table 5). This resulted in a viscosity within the acceptable range albeit on the low side. The stability was also improved by adding in one more emulsifier, steareth-2, with a low HLB value as suggested in Table 7. The cream texture was acceptable and it successfully passed through two freeze–thaw cycles. The prototype was further optimized but the details are omitted here. In parallel, prototype 3 was used in performance tests.

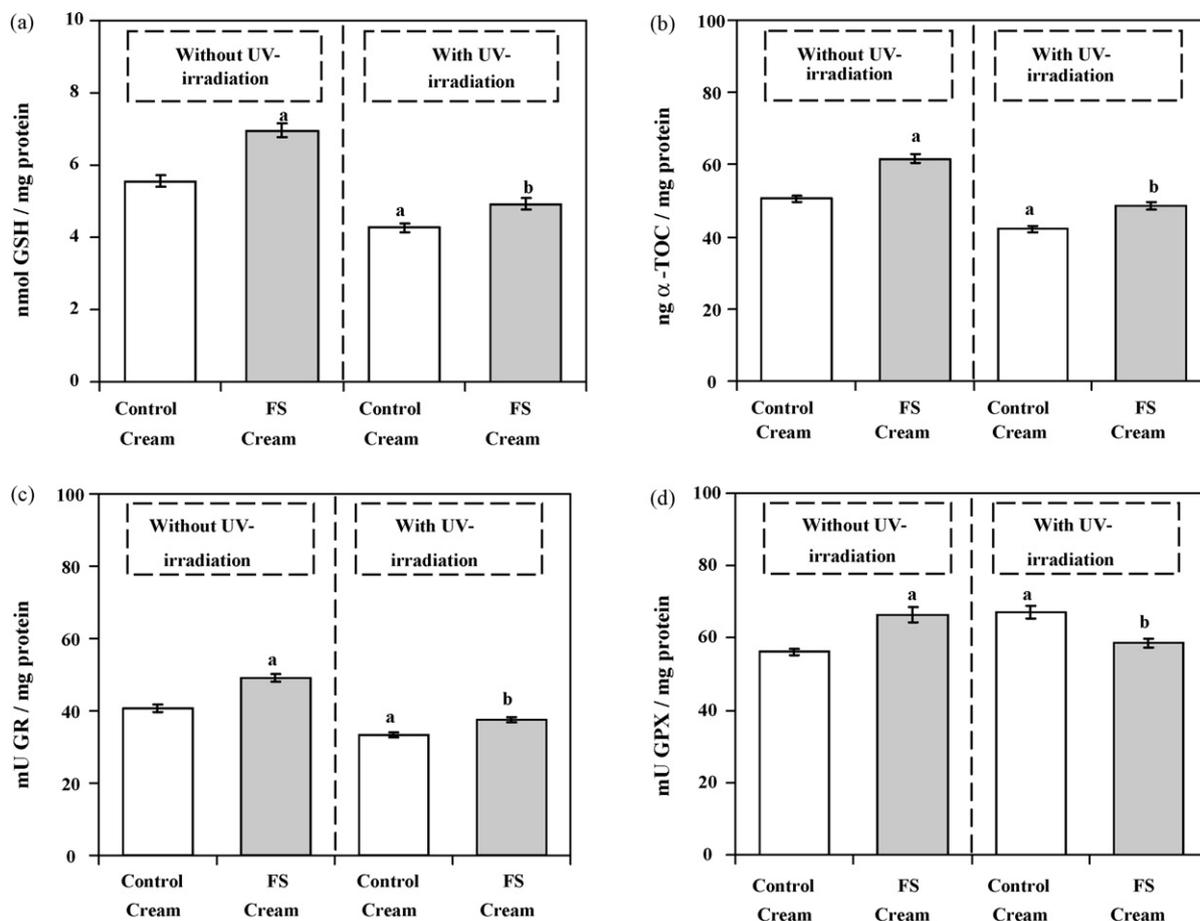
#### 7.1.4. Performance tests

The objective of performance tests is to verify, quantitatively if possible, the sun-screening, antioxidant and moisturizing functions of the product. These tests can be performed in-house but often they are eventually carried out by external testing laboratories that can certify the results. The degree of sun protection is quantified in terms of the SPF value. Some commercial skin analyzers are available to carry out various tests, such as skin surface hydration, serum content, pH, melanin erythema, transepidermal water loss, skin temperature, etc. (Leyden & Rawlings, 2002). Relative modifications should be designed if the performance of the prototype does not meet the target values. Only the antioxidant function and SPF value for the selected prototype are reported here.

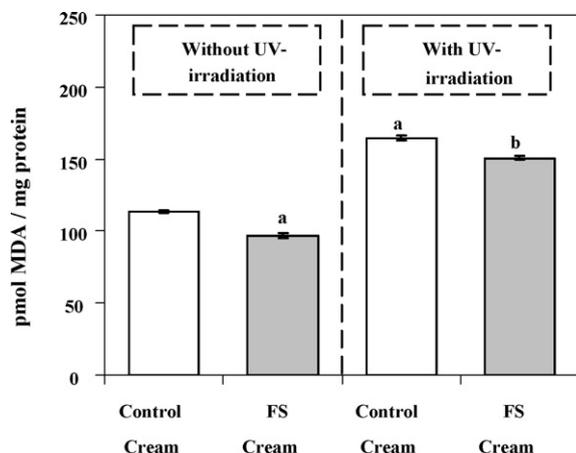
**7.1.4.1. Animal test.** A bioassay using rats was established for assessing the biological activity of the antioxidant-supplemented



**Fig. 5.** Schematic diagram of animal model for testing the antioxidant effect of topically applied cream on skin without or with UV-irradiation.



**Fig. 6.** Effect of topical FS cream pretreatment on the antioxidant status of rat skin tissue, without or with UV-irradiation. The antioxidant status of skin tissue after the UV-irradiation, was assessed by measuring (a) reduced glutathione (GSH), (b)  $\alpha$ -tocopherol ( $\alpha$ -TOC) levels, (c) glutathione reductase (GR) and (d) glutathione peroxidase (GPX) activities. Values given are mean  $\pm$  S.E.M., with  $n = 4$ . <sup>a</sup>Significantly different from the control cream without UV-irradiation; <sup>b</sup>significantly different from the control cream with UV-irradiation.



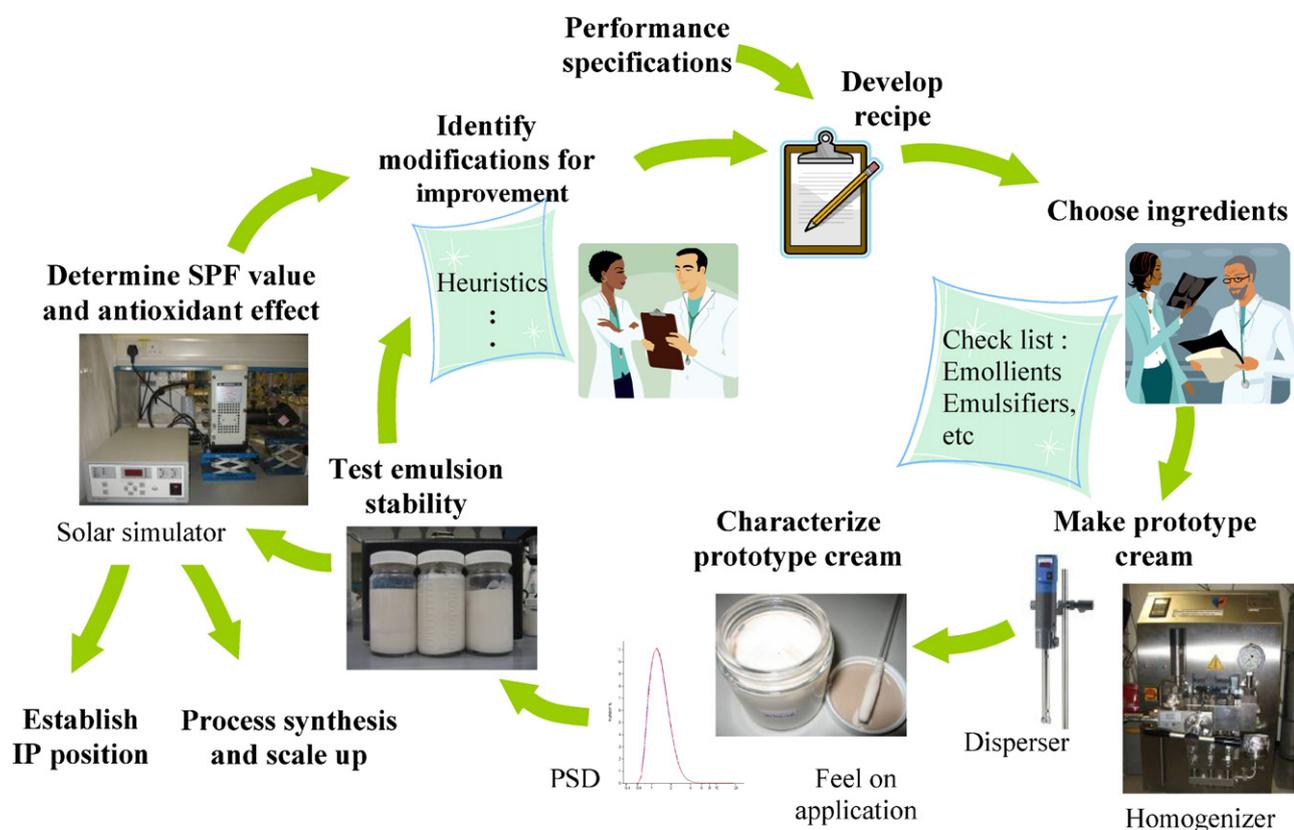
**Fig. 7.** Effect of topical FS cream pretreatment on of rat skin tissue, without or with UV-irradiation, as measured by malondialdehyde production. Values given are mean  $\pm$  S.E.M., with  $n=4$ . <sup>a</sup>Significantly different from the control cream without UV-irradiation; <sup>b</sup>significantly different from the control cream with UV-irradiation.

sunscreen. In this proof-of-principle study, two formulations of sunscreen, without or with supplementation with antioxidants derived from *Fructus Schisandrae*, were examined for their effects on the antioxidant status of rat skin tissue, without or with solar UV-irradiation. The enzymes that regenerate GSH from its oxidized form and decompose peroxides are glutathione reductase (GR) and glutathione peroxidase (GPX), respectively. These two enzymes are active and inducible upon oxidative stress. Topical application of

antioxidant containing cream can diminish such oxidizing damage arising from UV-irradiation. This animal test aimed to investigate the antioxidant ability of *Fructus Schisandrae*-containing cream product by measuring the levels of GSH and  $\alpha$ -TOC and the activities of GR and GPX after UV-irradiation. The results were compared with that of a control cream which was made based on the same procedure and formulation but without *Fructus Schisandrae* extract.

Adult female Sprague–Dawley rats were used in the experiment. Following an intraperitoneal injection of chloral hydrate at 350 mg/kg for short-term anesthesia, the animals were shaved on their back with an electric shaver followed by the application of hair removal cream. Two circular areas (37 mm in diameter) were marked on the shaved area. Each circle was divided into two semicircles as shown in Fig. 5. An amount of 200 mg of FS cream was applied to each of the two left semicircles, and the same amount of control cream was applied on the two right semicircles. The creams were applied once daily on the corresponding areas for 6 days. On the 7th day, the creams were applied 1 h before UV-irradiation, and the rat was anesthetized by an intraperitoneal injection of phenobarbital (120 mg/kg). A solar simulator (Oriel #96000, 150-W) with an output of 10.88 mW/m<sup>2</sup> of UVA light (320–400 nm) and UVB light (290–320 nm) was used. The rat was placed 5 cm underneath the light source for 30 min so that the UV light could fall on the lower circular area on the back as shown in Fig. 5, while the upper part was shielded by black paper and aluminum foil. After the UV exposure, the rat was killed by cervical dislocation, and skin tissues (epidermis and dermis) of the four areas were isolated from the rat. Skin tissue samples were homogenized followed by centrifugation. The supernatants were subjected to biochemical analyses on the level of non-enzymatic and enzymatic antioxidants.

## Workflow for Skin-Care Cream Prototype Fabrication



**Fig. 8.** Workflow diagram for iterations between choosing formulation ingredients and performance testing.

**Table 9**  
A RAT<sup>2</sup>IO module for prototype fabrication.

Objectives	Input information	Activities	Tools	Resources	Time (week)	Output information
4.4.1 Develop a base case formula	Technical specifications	Measure physical and chemical properties of active ingredients	–	Formulators	2	Physical and chemical properties of active ingredients Base case formula
	Product microstructure Selection guidelines for supporting materials Government regulations on prohibited materials Sample recipes/formulae Ingredients checklist	Choose supporting materials Design prototyping procedure		Scientists		
4.4.2 Prepare a stable prototype cream	Heuristics for formula modification	Prepare cream prototype	Stir plates	Formulators	20 <sup>a</sup>	Prototype cream formula, fabrication procedure and a sufficient amount of sample
	Physical and chemical properties of active ingredients Base case formula	Check particle size distribution  Check emulsion appearance Test the feel on application Check emulsion stability Modify prototype formula	Hand-held mixers  Disperser Homogenizer Viscometer pH meter Particle size distribution analyzer	Scientists  Test panel Technicians		
4.4.3 Test product performance	Prototype cream formula Heuristics for formula modification	Check antioxidant effect  Check SPF value Check moisturizing effect Fine tune concentration of active ingredients	Solar simulator  Animal model Bioassay Skin analyzer	Formulators  Scientists Test panel Technicians	9 <sup>b</sup>	Prototype formula with refined concentration of active ingredients

<sup>a</sup> The total duration was calculated by assuming 20 inner loop iterations in the workflow of prototype fabrication (Fig. 8), and each loop took an average time of 1 week.

<sup>b</sup> The total duration was calculated by assuming 3 outer loop iterations in the workflow of prototype fabrication (Fig. 8), and each loop took an average time of 3 weeks.

The details of sample preparation procedure of such biochemical analyses have been described elsewhere (Chiu, Mak, Poon, & Ko, 2002).

Topical treatment with FS cream caused an improvement in antioxidant status of skin tissue, as evidenced by significant increases (18–25%) in tissue GSH and  $\alpha$ -TOC levels, as well as increases in GR and GPX activities, when compared with those treated with control cream containing no FS (Fig. 6a–d). UV-irradiation depleted antioxidants in skin tissue to varying extents (16–23%), except for GPX which showed a significant increase in enzyme activity (16%), an indication of increased oxidative stress. The beneficial effect of FS cream on skin tissue became more apparent after UV-irradiation. The UV-induced depletions of skin antioxidants were significantly ameliorated by FS cream pretreatment. The enhancement of antioxidant status of skin tissue by FS cream was further evidenced by the measurement of tissue malondialdehyde (MDA) production, an indirect index of free radical-induced oxidation of lipids. While FS cream treatment decreased the extent of MDA production (by 15%) in skin tissue without exposing to UV, it also suppressed the UV-induced increase in MDA production (by 10%) (Fig. 7).

**7.1.4.2. SPF test.** The SPF test procedure was simplified from the method suggested by FDA (Food & Drug Administration, 1978). For a light source with a fixed energy output, the SPF value is the ratio of the time to produce the minimal erythema dose (MED) on protected skin and that on unprotected skin:

$$\text{SPF} = \frac{\text{MED}_{\text{protected skin}}}{\text{MED}_{\text{unprotected skin}}} \quad (2)$$

The artificial light source was the same solar simulator used in animal test. The power of UVA and UVB at the exit port was measured as  $3.891 \times 10^{-3} \text{ W m}^{-2}$  and  $3.518 \times 10^{-3} \text{ W m}^{-2}$ , respectively.

Test sites on the arm of a volunteer were used for reason of convenience. Four sites, 2.5 cm in diameter each, were marked with ink. They were exposed to the exit port of the instrument for 60 s, 75 s, 94 s, and 117 s, respectively. Other areas were covered by black cardboard. The sites were inspected 24 h later for the intensity of erythema. For this volunteer, minimal erythema was observed on the test site which had been exposed for 94 s and this was recorded as the MED for unprotected skin.

Test sites on the other arm of the same volunteer were used for determining MED for protected skin. According to the zinc oxide supplier, a day cream containing 9.6% ZnO would result in an SPF of around 8. Thus, the time for the MED of protected skin was expected to be around 752 s (i.e.,  $8 \times 94$  s). 2 mg/cm<sup>2</sup> of the prototype cream was applied on three test sites at least 15 min before UV exposure. Then the protected sites were exposed to same UV intensity for 420 s, 600 s and 752 s, respectively. Again, the rest of the arm was covered with black cardboard. Erythema was observed on the site with 600 s exposure, resulting in an SPF value of 6.4 which does not meet our target value of 8–15 (Table 3). Clearly, more subjects should be used to increase the accuracy and an increase in the concentration of zinc oxide should be considered. These detailed will not be further discussed here.

## 8. Conclusions

Product development is a hierarchical, multiscale, multidisciplinary and iterative activity. It is hierarchical in the sense that decision-making progresses from objective to subjective with increasing levels of details, while keeping in mind the overall product development project. The objective-time chart (Fig. 2) reflects this hierarchical thinking, which is in a way a simple extension of the hierarchical process design method proposed by Douglas

(1988). Also well-recognized is the multiscale nature of product development in that the time and length scales of the relevant physicochemical phenomena, production activities, and logistics and transportation beyond the manufacturing plant differ by orders of magnitude (Charpentier, 2007; Grossmann & Westerberg, 2000; Lerou & Ng, 1996). Product development inevitably involves professionals in sales and marketing, law, project management, advertising, and financial analysis. This multidisciplinary nature is captured in Fig. 1 where the activities in product development are classified by phase and by job function, and several unit tasks are identified. In fact, on the technical side, there are also chemical-based products in science and engineering areas such as medicine, healthcare, foods, electronics and information technology that are not the primary domain of a typical chemical engineer. The need for iterations in product development is represented by the workflow diagram (Fig. 3). A product that warrants the significant investment associated with product launch demands detailed consideration from all angles.

To achieve product development with the least amount of time, effort and money, we believe systematic product development procedures and methods are essential. This skin-care cream case study provides a concrete example to illustrate the multitude of issues. On product conceptualization, chemical engineers have to actively collaborate with other professionals on business decision-making. While science and engineering can address how-to-make by selecting suitable materials and processing techniques, what-to-make inevitably involves marketing, IP position, and a host of environmental and safety issues. On research and development, the use of experiments, modeling and synthesis in an iterative manner is the key for prototyping.

The generic issues and approach for each unit task discussed in this paper are applicable for developing any given class of products. However, the heuristics, experiments and models are expected to be product class-specific. It is unlikely that the development team can come up with the best execution plan for a new product if the team does not have previous experience in working with the relevant line of products. In fact, the final objective-time chart (Fig. 4) and the RAT<sup>2</sup>IO module for the overall skin-care cream development project (Table 1), and the workflow diagram for iterations in prototype fabrication (Fig. 8) and the corresponding RAT<sup>2</sup>IO module (Table 9) actually took shape towards the end of this study. Nonetheless, these can certainly be used to expedite the development of similar products in the future. The importance of performance tests in product development was demonstrated. A bioassay, which involved live skin preparation, was essential for assessing the antioxidant activity of the cream formulation. Along with measurements for the sun-screening and moisturizing functions, they serve as measures for optimizing the formulation of sunscreen cream.

As the scope of the chemical industry expands from commodity chemical business to include the manufacture and sale of higher value-added products, many new opportunities emerge for chemical engineers to contribute in product development. An obvious question would be, what are the market segments that chemical engineering as a profession would like to engage in? A similar question was posed by the processing community in China (Ng, Li, & Kwauk, 2005). In addition, in each market segment, what are the tasks that a chemical engineer would like to and can perform? These questions have ramifications in what we consider to be a typical chemical engineering curriculum. The possible inclusion of business subjects in a chemical engineering education has been discussed by Landau (1997), Ng (2002), Ng and Wibowo (2003) and Wei (2008). The concept of unit operations has served process design well by providing the building blocks for process flow-sheeting. Now, can the concept of unit tasks with their associated

RAT<sup>2</sup>IO modules, properly defined, categorized and enriched with the necessary technical as well as non-technical details, serve as the building blocks for product development? Efforts to address some of these issues are underway.

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